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System reliability approach for rock scour

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ABSTRACT

Removal of individual blocks of rock is one of the principal mechanisms by which scour can occur, and prediction of block erodibility can be complicated due to the inherent variability associated with the rock mass as well as flow conditions in the vicinity of the block(s) in question. In order address the stochastic nature of the problem, we present a methodology for system reliability assessment of the probability of scour of 3D rock blocks subject to hydraulic loads within a block theory framework. Monte Carlo simulations are used to determine overall block failure probability, and to identify the most likely failure mode. A first-order reliability method (FORM) is then used to determine sensitivity to the different variables and hence the relative level of importance of the physical parameters with respect to the dominant failure mode. An example problem is used to illustrate the value of this information in focusing site investigations and analyses on the most important variables as well as in guiding decisions regarding scour mitigation strategies.

1. Introduction

Scour of rock is an issue for critical infrastructure such as dams, bridges and tunnels, where excessive erosion of the structure's foundation can compromise stability, leading to high remediation costs or even loss of life should catastrophic failure occur. Accordingly, reliable quantification of rock erodibility is necessary to ensure the continued, safe operation of these structures. The removal of individual blocks of rock by hydraulic forces is one of the primary mechanisms by which rock scour can occur. Prediction of block erodibility, however, is hindered by the inherent variability associated with the rock mass comprising the foundation/spillway as well as with flow conditions in the vicinity of the block.

To account for this variability, a system reliability approach for block stability is implemented. In recent years, risk and reliability methods have seen increased use among practitioners and researchers for quantification of event failure probability to aid in hazard analysis and the decision-making process. However, these studies have had limited use in the current state-of-the-art rock scour prediction models, e.g., Refs. 1–3. Reliability methods have been successfully applied to general rock slope stability in 2D,[4] and for 3D rock wedges defined by two discontinuity planes in Refs. 5–7. We extend the systems reliability approach to 3D rock blocks bound by three discontinuity planes and one free face. While the analysis is presented for hydraulic loading by channel flow, the method can be readily applied to block stability problems of similar geometry with other loading conditions (e.g., gravity, seepage, overtopping jet).

2. Model formulation

Material properties and processes in most geologic settings are inherently variable and accordingly a probabilistic approach is a natural choice for their evaluation. Quantification of the rock scour process requires a joint assessment of the erosive capacity of water and the resistive capacity of the rock mass. Variability in erosive capacity is predominantly produced by unsteadiness and turbulent flow conditions, which can change both spatially and temporally; while variability in rock block resistance is dominated by the spacing, orientation and shear strength (friction and dilation angle) of the discontinuities bounding the block (Fig. 1).

Removal of individual blocks of rock is one of the principal mechanisms by which scour occurs in unlined rock channels/tunnels, bridge foundations, dam abutments, and plunge pools. The discontinuities around the block allow for transmission of hydraulic pressures to the block faces that can result in removal (failure) (Fig. 2). For 3D blocks, there are a number of kinematic failure modes that lead to a block being removed from its mold.[8] These consist of pure translational movements (e.g., lifting, one-plane sliding, or two-plane sliding), pure rotational movements (e.g., about an edge, about a corner, or about an arbitrary point), or

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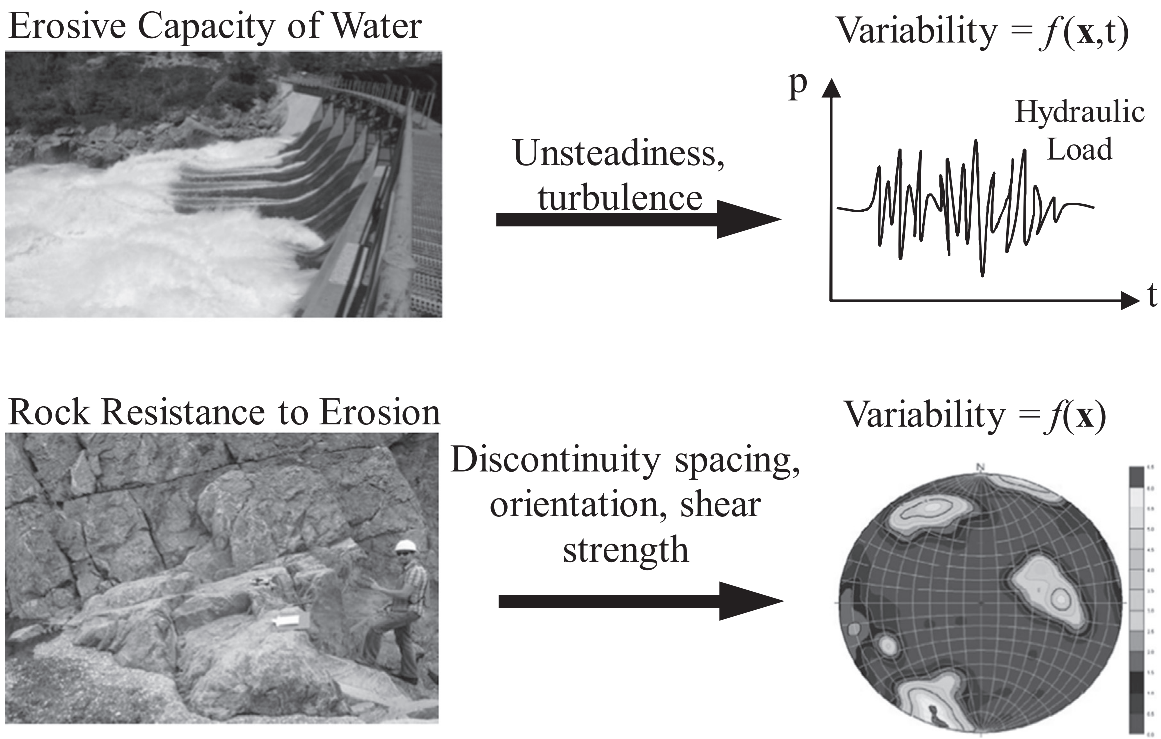

Fig.1. Variability in the rock scour process.

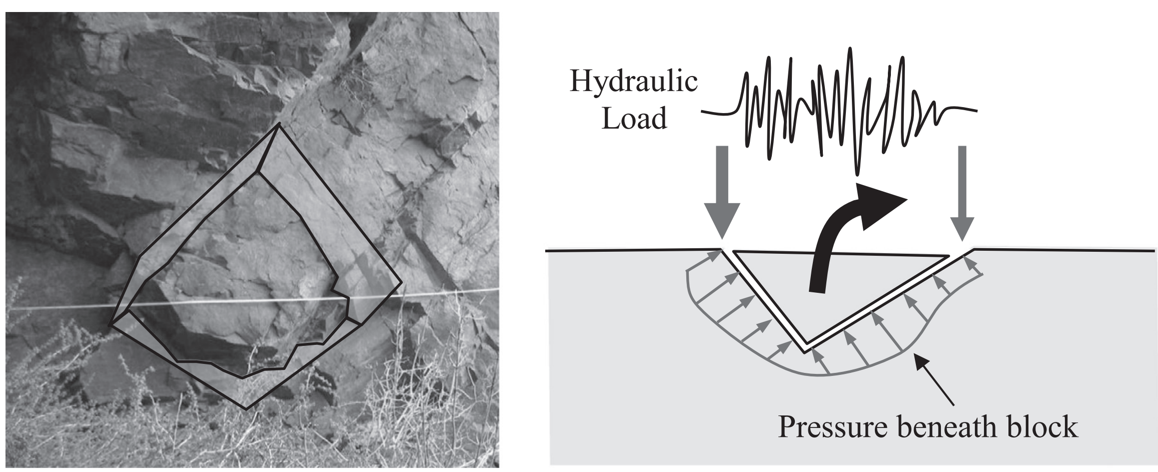

Fig. 2. Rock block as defined by surrounding discontinuities (left) and schematic for block removal due to transmission of hydraulic pressures beneath block (right).

some combination of translation and rotation (Fig. 3).

Failure of a removable block[9] in a particular failure mode is subject to several kinematic constraints that must be satisfied for a block to be eroded. For tetrahedral rock blocks, the number of kinematic failure modes and the probability that the block is removable and rotatable is fairly low[10] since the number of failure planes is limited to 3. Accordingly, for the example analysis presented below, we only consider the pure translational modes (lifting, 1-plane sliding, and 2-plane sliding).

For pure translation modes, lifting of a block is kinematically feasible when

$$\mathbf{s}\cdot\mathbf{v}_i > 0, \text{ for all } i \tag{1}$$

where **s** is the direction of block movement (equal to the direction of the active resultant, **r**, for lifting), and $\mathbf{v}_i$ is the block-side normal vector for the ith joint plane. **Bold** font signifies a vector/matrix quantity. This condition ensures the block moves away (lifts) from each of the bounding joint planes. The block-side normal may be calculated by

$$\mathbf{n}_i = \begin{bmatrix} \sin(\delta_i)\cdot\sin(\theta_i) \\ \sin(\delta_i)\cdot\cos(\theta_i) \\ \cos(\delta_i) \end{bmatrix},$$

$$\mathbf{v}_i = \mathbf{n}_i \text{ (block is above } i\text{th joint plane), or}$$

$$\mathbf{v}_i = -\mathbf{n}_i \text{ (block is below } i\text{th joint plane),} \tag{2}$$

where $\mathbf{n}_i$ is the upward normal for the ith joint plane and δ_i, θ_i are the dip and dip direction, respectively, of the ith joint plane. For block sliding on plane i only, the sliding direction is given by:

$$\mathbf{s} = \mathbf{s}_i = \frac{(\mathbf{n}_i \times \mathbf{r}) \times \mathbf{n}_i}{|\mathbf{n}_i \times \mathbf{r}|} \tag{3}$$

This is the orthographic projection of the active resultant force vector, **r**, onto the sliding plane. Kinematic feasibility of 1-plane sliding is subject to the following constraints: